Simple Scaling Of Multi-Stream Jet Plumes For Aeroacoustic Modeling

James Bridges
NASA Glenn Research Center

AIAA SciTech 2016 Conference – 4-8 Jan 2016

Supported by
NASA Advanced Air Vehicles Program/Commercial Supersonics Technology Project
Thanks to Mark Wernet, Brenda Henderson, Gary Podboy for data.

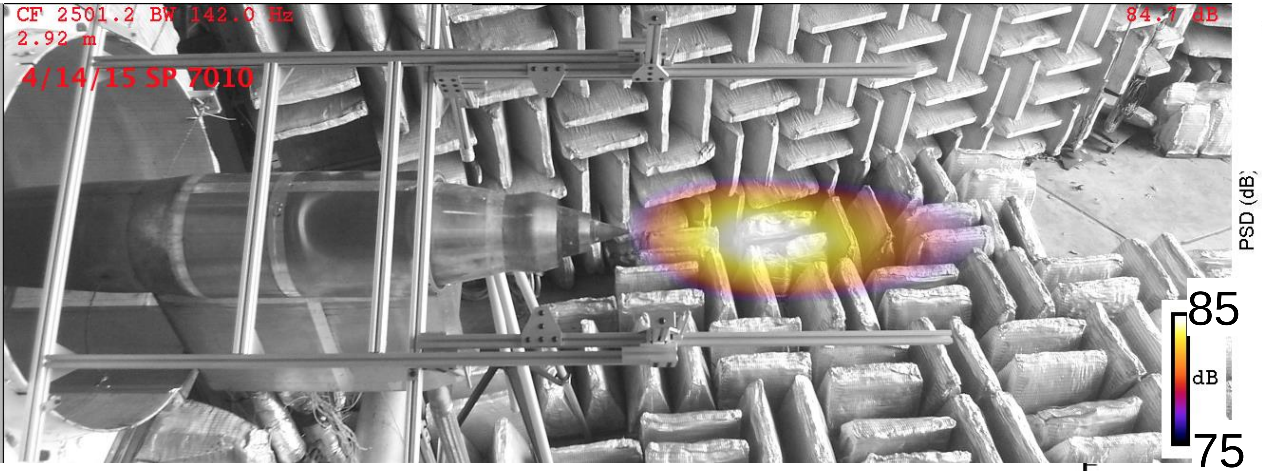
Challenge: Design supersonic airliner that is acceptable in range, sonic boom, airport noise, and engine emissions.

Note: System optimization key—design trades are critical.

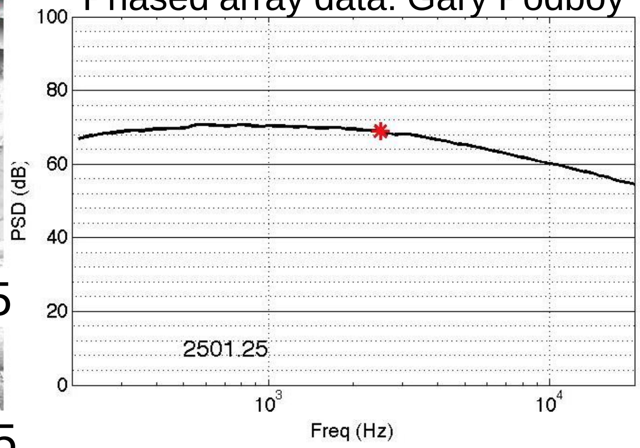
Note: **If you don't give the system analysts a noise prediction model they will make one up for themselves.**

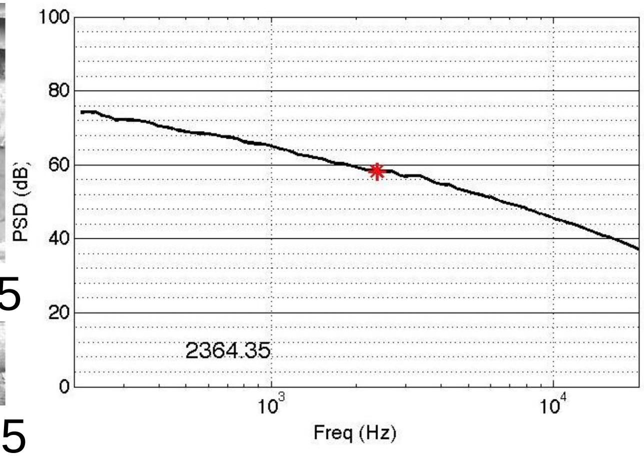
Modeling jet-installation effects—shielding

- Phased array source distributions; note amplitude scales!
- Ma = 0.9, unheated jet with and without simple surface at significant standoff
- First order effect—line of sight blockage



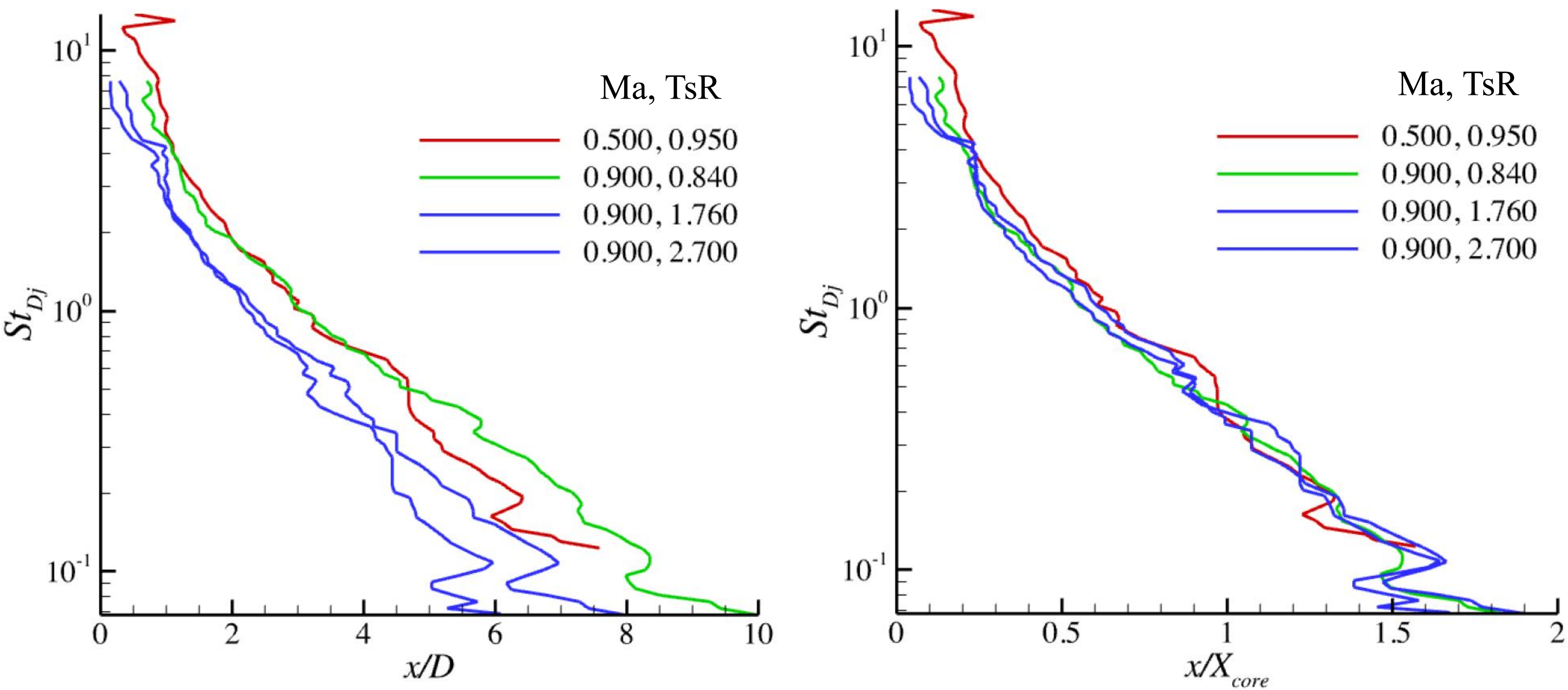
Phased array data: Gary Podboy





Source location modeling

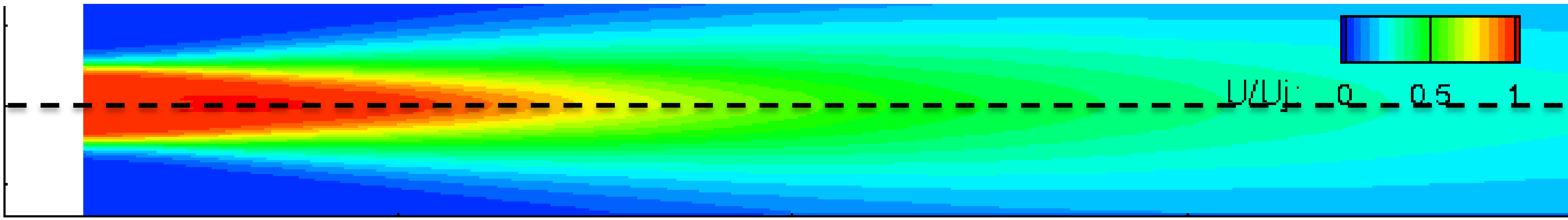
- Brown's modeling approach for JSI shielding with single stream jets, simple nozzles:
  - Suppression is function of surface length relative to source location
  - Source location is related to potential core length X_{core}= f(Mj, Tj)
  - Suppression modeled by L/D relative to X_{core}.

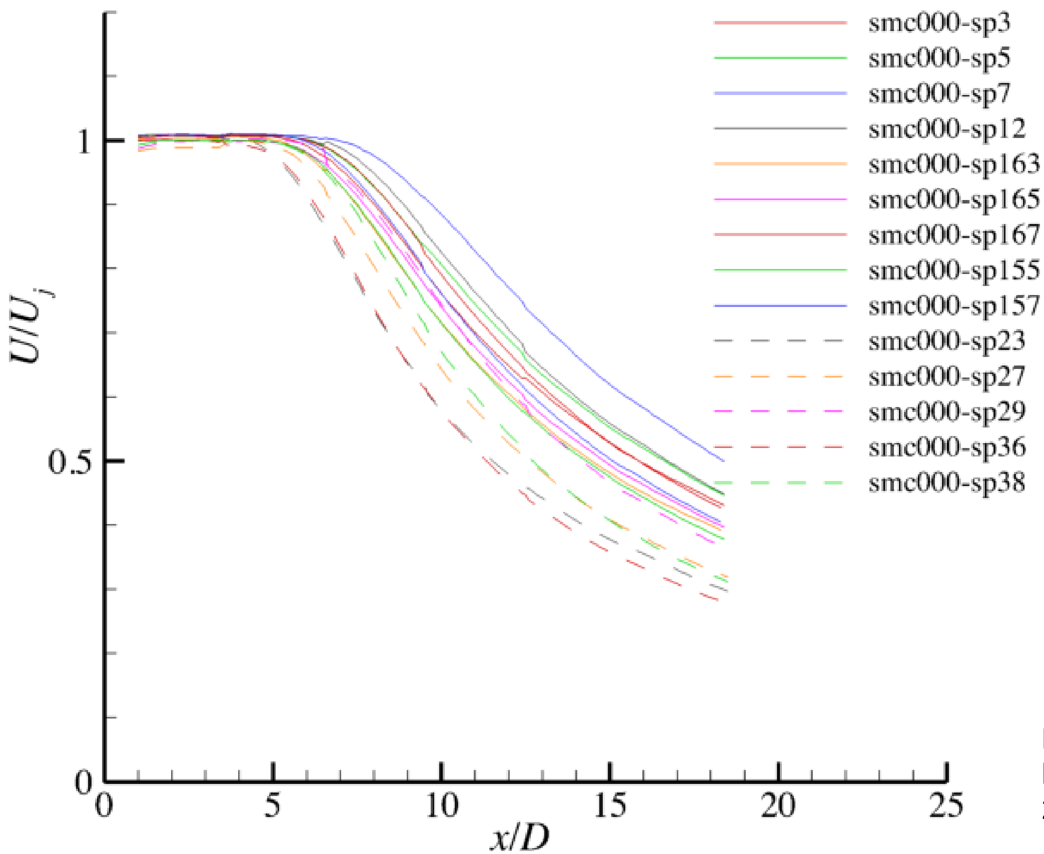


Podboy, G.G., "Jet-Surface Interaction Test: Phased Array Noise Source Localization Results," GT2012-69801, (2012)

Jet Plumes—Mean Centerline Profile

- Typical centerline velocity for single stream from simple nozzle





Variation in jet conditions:
0.5 < *Ma* < 1.33
0.85 < *TsR* < 2.27

Bridges, J. and Wernet, M.P. "The NASA Subsonic Jet Particle Image Velocimetry (PIV) Dataset," NASA/TM—2011-216807, (2011).

Scaling of Jet Plumes—2-parameter model

- Elegant model for mean velocity on centerline

$$\phi = \frac{U - U_\infty}{U_j - U_\infty} = 1 - \exp\left\{\frac{\alpha}{1 - \frac{x/D}{\beta}}\right\}$$

- α is exponential decay, β is potential core length
- Parameters α, β obtained by fitting line to

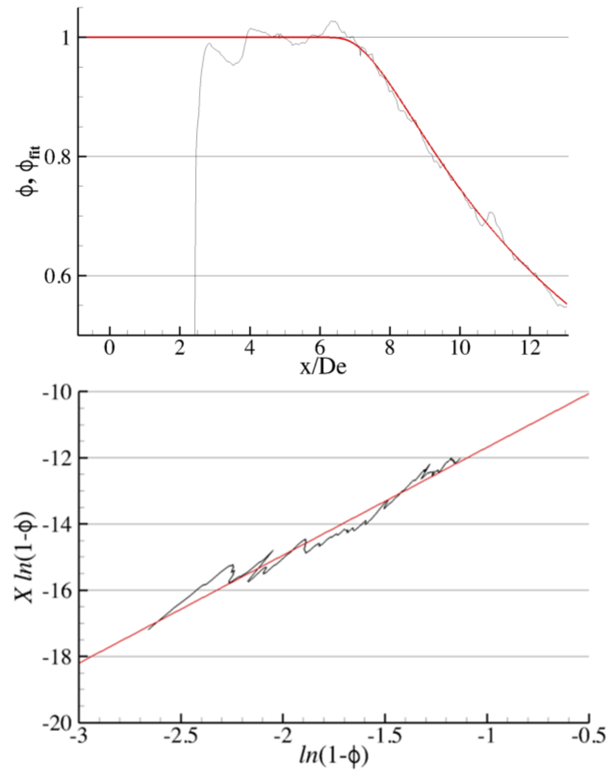
$$X\, ln(1-\phi) = \beta\, ln(1-\phi) - \alpha\beta$$

- For single jets α, β modeled in terms of *Mj*, *TsR*

$$\alpha = \frac{-1.848(1-0.25M_j)}{TsR^{0.4}}$$ *(= 1.43 for Witze)*

$$\beta = \frac{3.195(1+0.796M_j)}{TsR^{0.11}}$$

- Referred to as Simple Single-Stream (SSS) model



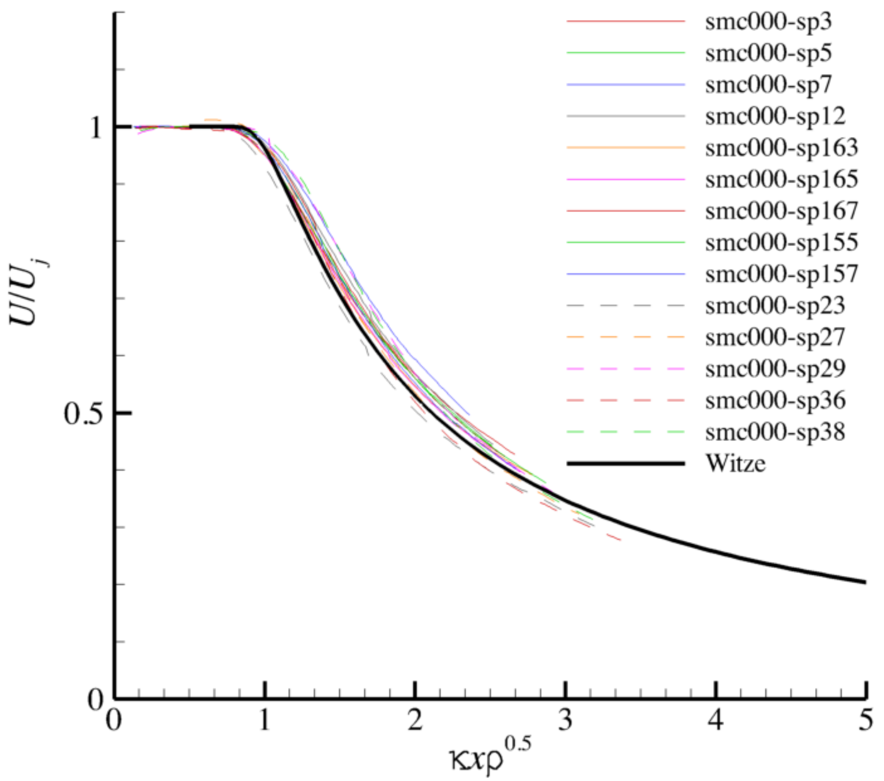
Witze, P.O. "Centerline Velocity Decay of Compressible Free Jets," AIAA Journal, Vol. 12, No. 4, (1974).

Simonich, J.C., Narayanan, S., Barber, T.J., Nishimura, M. "Aeroacoustic Characterization, Noise Reduction, and Dimensional Scaling Effects of High Subsonic Jets," AIAA Journal, Vol. 39, No. 11, (2001).

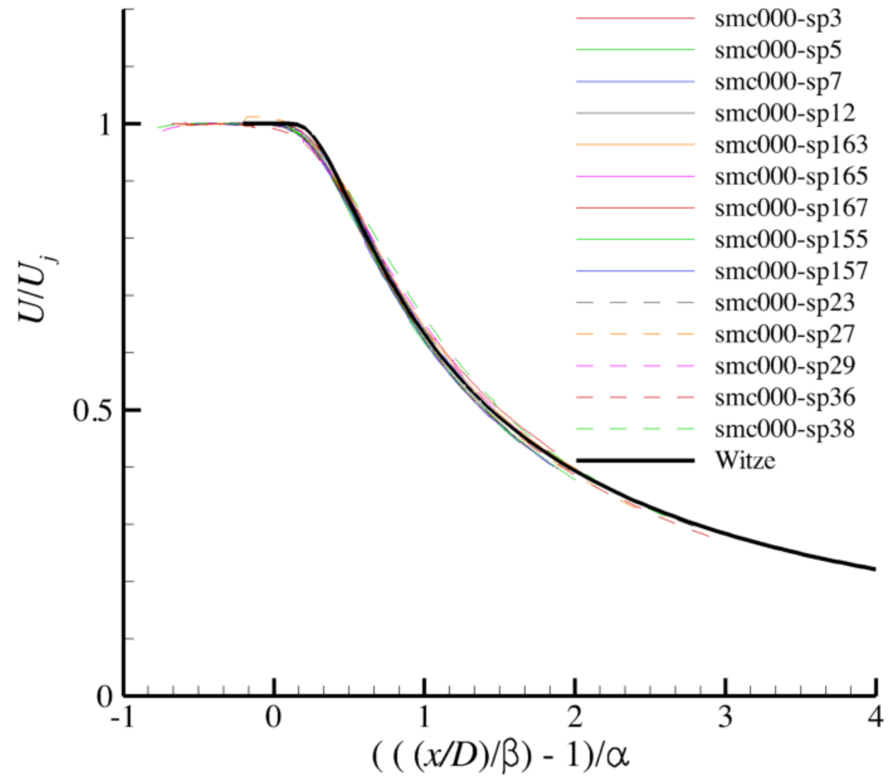
Witze (1-parameter) vs SSS (2-parameter)

- Decay is not universal as assumed by Witze (Kleinstein)
- SSS model captures decay better
- 2-parameter models can be created for other effects (chevrons, non-axisymmetric nozzles, etc.)

Centerline axial velocity—Witze scaling



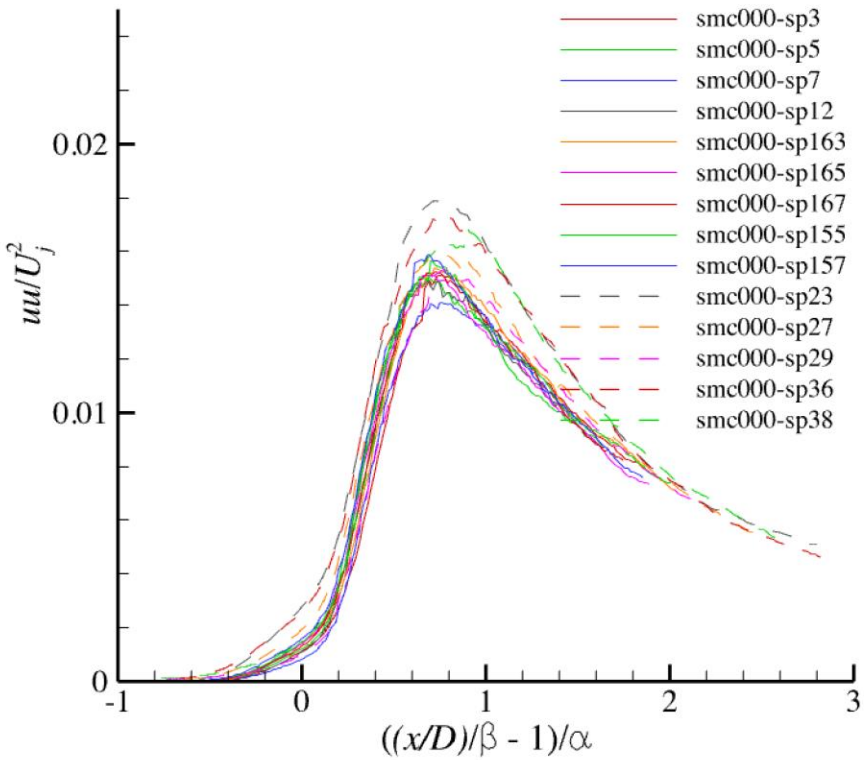
Centerline axial velocity—SSS scaling



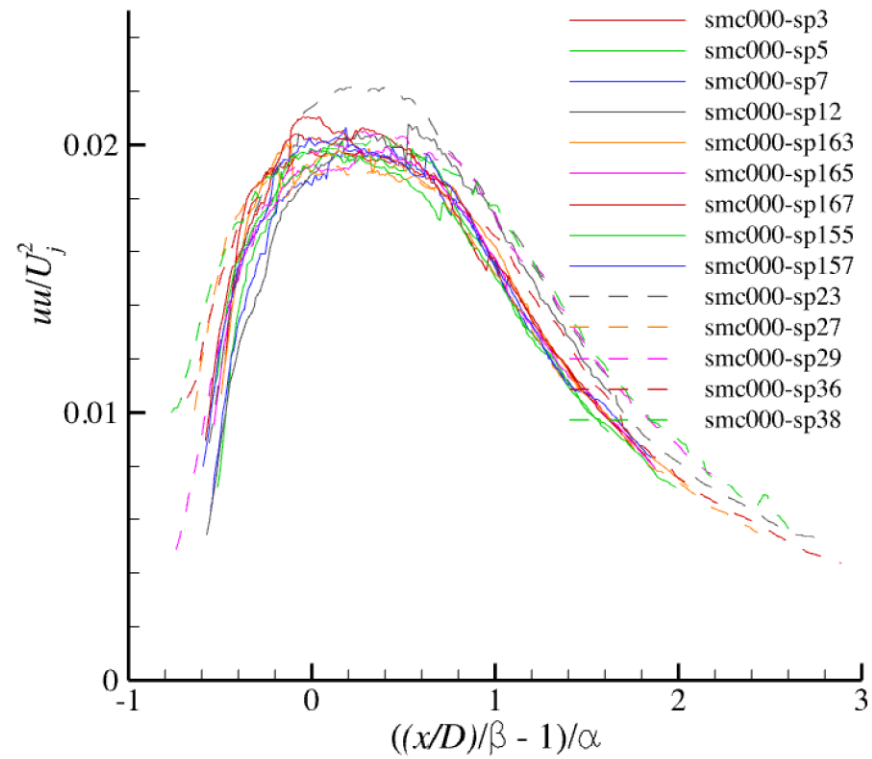
Why this works for noise source distribution—Collapse of peak turbulence

- Turbulent velocity distributions collapse as well

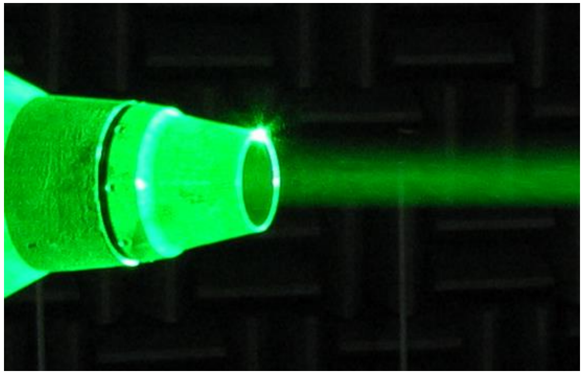
Centerline

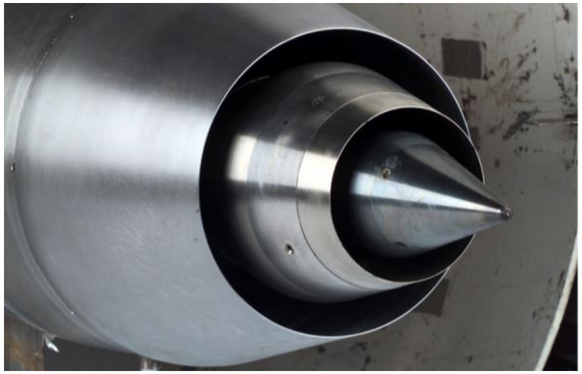


Lipline



Extension to Multiple Stream Nozzles?

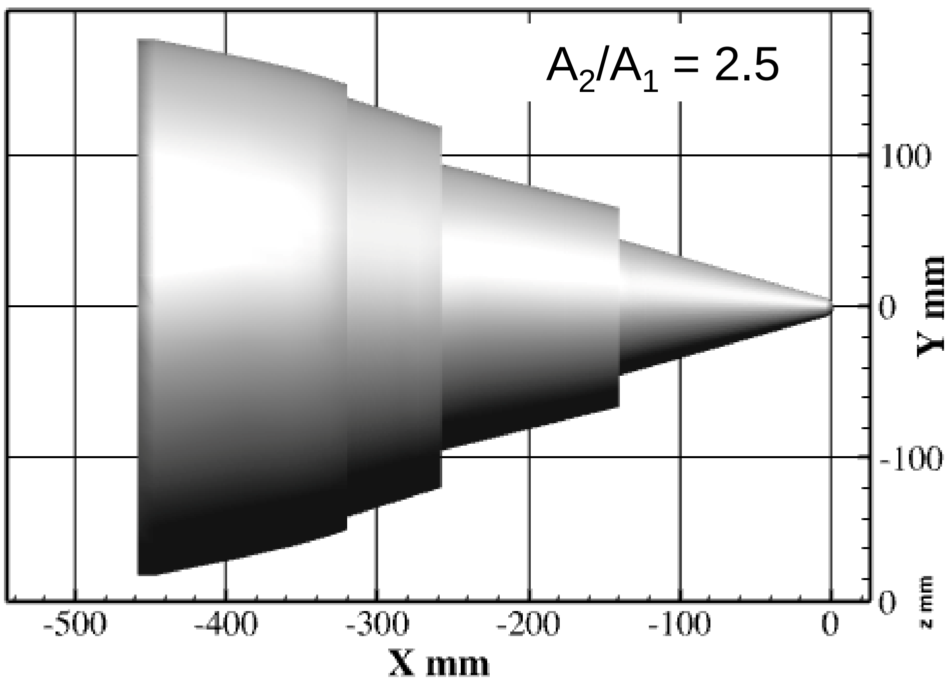


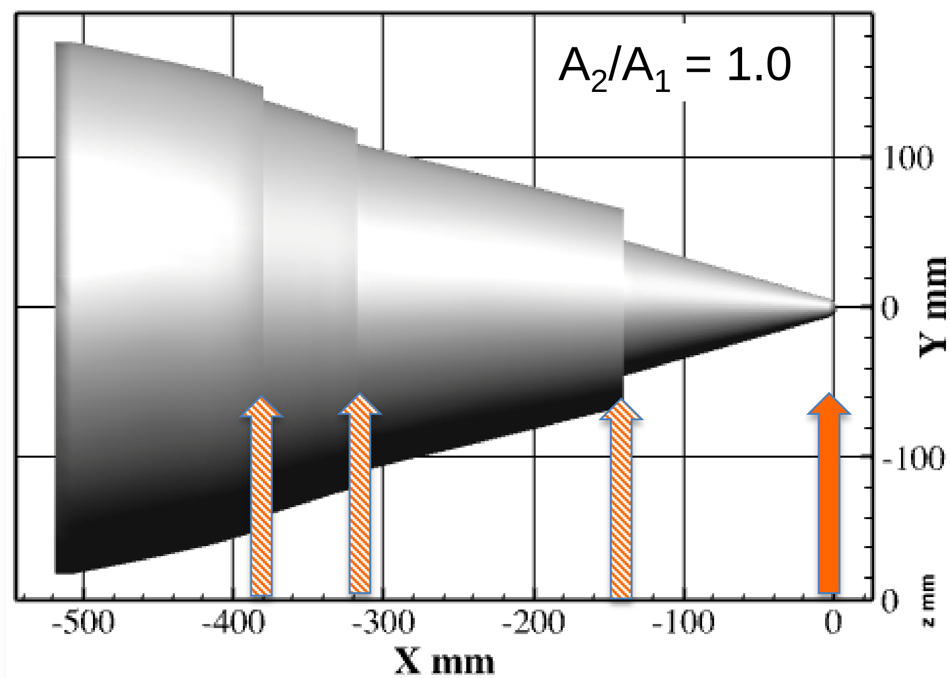


- Can we model source distributions of multiple stream jets by finding equivalent potential core and decay?
  - Equivalent origin x_0, diameter *De* for complex nozzles?
  - Equivalent flow conditions *Ma*, *TsR* for multiple stream jets?
- Can proper selection of x_0, *De* , *Ma, TsR* produce collapse of multiple stream plumes when plugged into model equations for single-stream jet?

Three-stream PIV Dataset--Nozzles

- Henderson & Wernet AIAA SciTech2016 (preceding talk)
- Axisymmetric, externally mixed, external plug nozzles
- Three combos of area ratios, $A_2/A1$ = 1.0, 2.5; A_3/A_1 = 0.6, 1.0
- Note lack of clear definition of plume origin, diameter
  – Origin: First flow nozzle? Minimum jet diameter?
  – Diameter: First flow nozzle? Total area?





Three-stream PIV Dataset—Flow Conditions

- Main dataset:
  - NPR_1 = 1.8, NTR_1 = 3.0,
  - NPR_2 = 1.8, NTR_2 = 1.25
  - 1.0 < NPR_3 < 2.1, NTR_3 = 1.25

nozID	setpoint	NPR1	NPR2	NPR3	NTR1	NTR2=NTR3	Mflight
C1T1	88033	1.8	1.8	1	3	1.25	0.3
C1T1	88433	1.8	1.8	1.4	3	1.25	0.3
C1T1	88833	1.8	1.8	1.8	3	1.25	0.3
C1T1	88133	1.8	1.8	2.1	3	1.25	0.3
C3T1	88033	1.8	1.8	1	3	1.25	0.3
C3T1	88433	1.8	1.8	1.4	3	1.25	0.3
C3T1	88833	1.8	1.8	1.8	3	1.25	0.3
C3T1	88133	1.8	1.8	2.1	3	1.25	0.3
C3T3	88033	1.8	1.8	1	3	1.25	0.3
C3T3	88433	1.8	1.8	1.4	3	1.25	0.3
C3T3	88133	1.8	1.8	2.1	3	1.25	0.3
C1T1	88430	1.8	1.8	1.4	3	1.25	0
C3T1	88430	1.8	1.8	1.4	3	1.25	0
C3T1	80010	1.8	1	1	1	1.25	0
C3T1	80030	1.8	1	1	3	1.25	0
C3T1	86010	1.8	1.6	1	1	1.25	0
C3T1	86210	1.8	1.6	1.2	1	1.25	0

Vary NPR3

Static

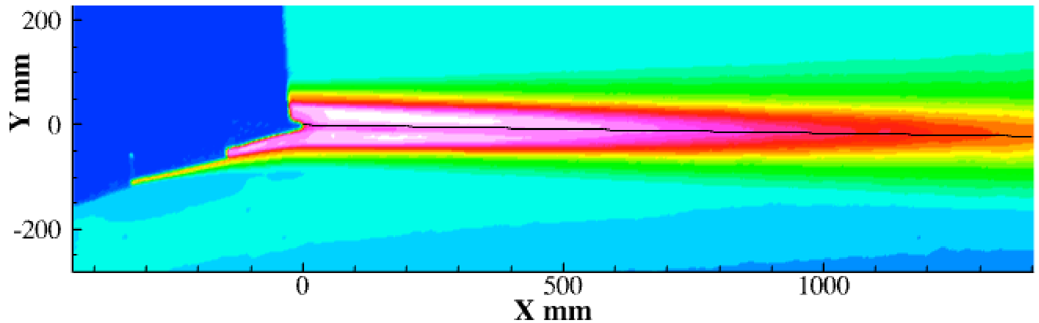
Single Stream

Isothermal

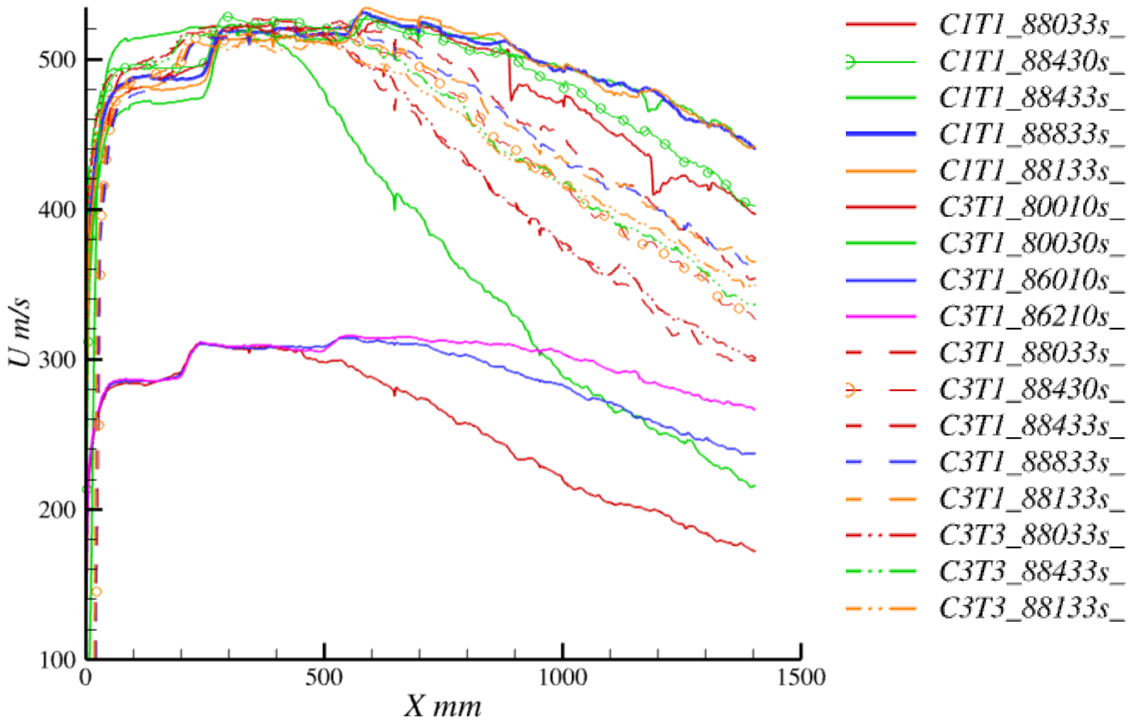
Extracting ‘centerline’ from PIV data

- Complications by presence of plug wake, experimental deviations from symmetry
- Objective is to find end of potential core and exponential decay

Typical contour plot of mean axial velocity

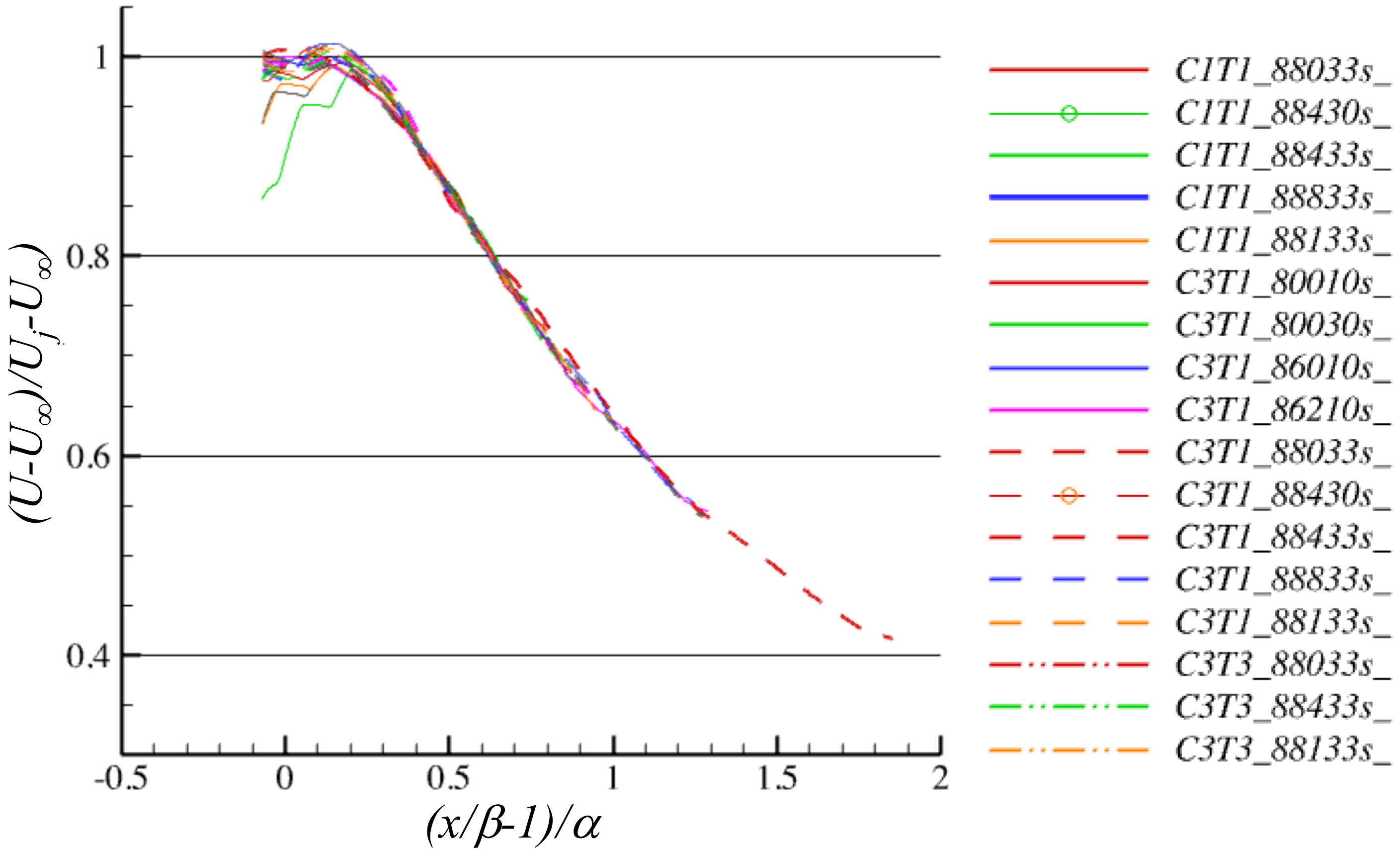


Extracted axial profiles of mean axial velocity, all PIV data studied



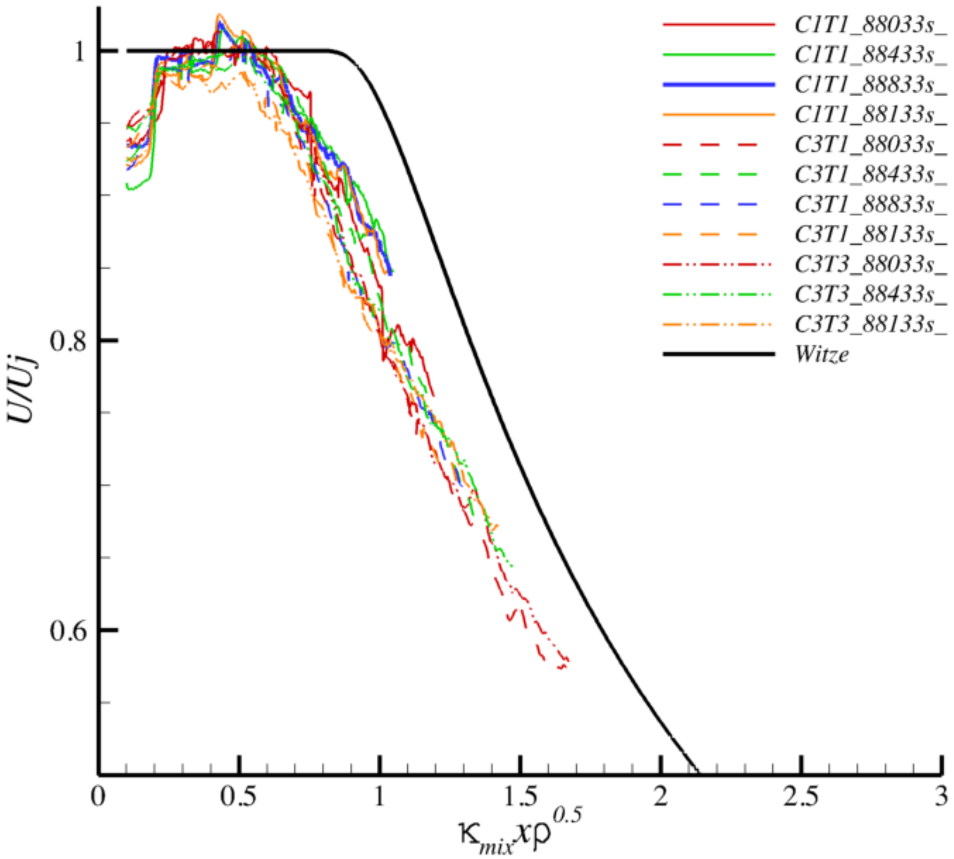
Scaling of Multi-Stream Plumes—Fitted α, β

- Using same procedure for fitting α, β to transformed profiles, multi-stream plumes collapse when plotted in normalized coordinates.
- Multi-stream plumes to have same shape!
- Can appropriate equivalent jet parameters plugged into models give similar collapse?



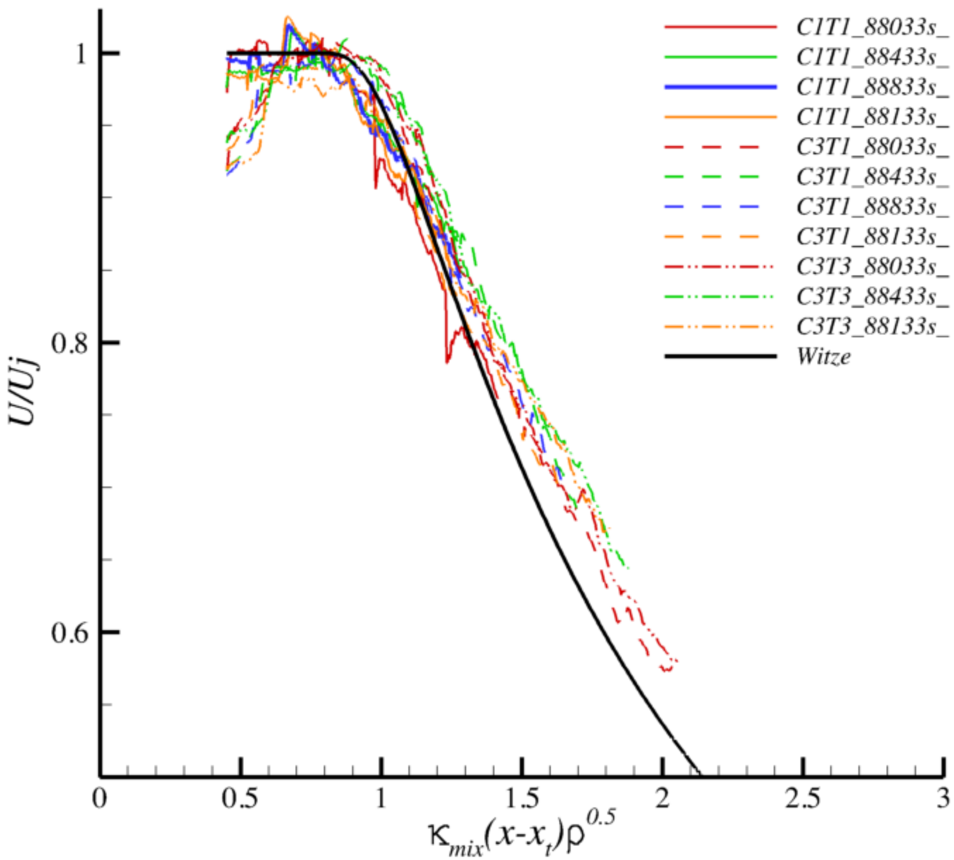
Collapse of centerline profiles—Witze model(1)

- Three area ratio combinations with several NPR_3 each.
- Using **mixed flow conditions** for Witze scaling
- Using **total flow area** for diameter and **plug tip** for origin.
- Collapse but not matching potential core length.



Collapse of centerline profiles—Witze model(2)

- Three area ratio combinations with several NPR_3 each.
- Using **mixed flow** conditions for Witze scaling
- Using **total flow area** for diameter and **first flowing lip** for origin.
- Matching potential core length.
- Not matching decay rate.

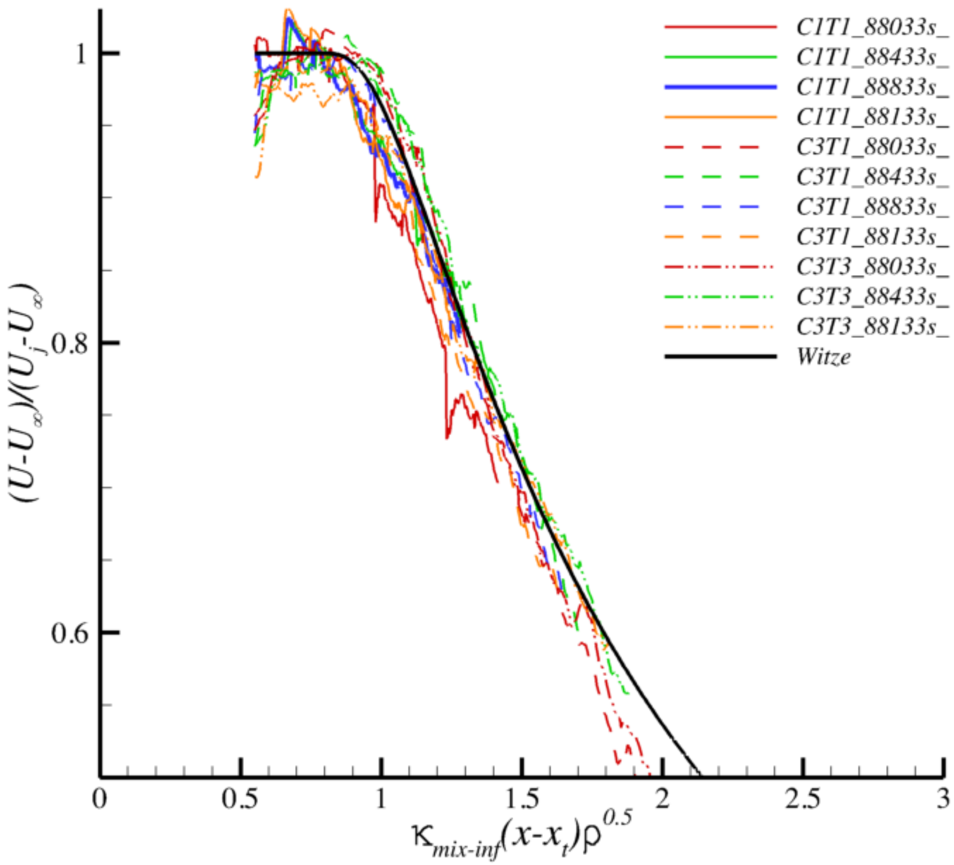


Collapse of centerline profiles—SSS model

- Three area ratio combinations with several NPR_3 each.
- Using ***relative* mixed flow** conditions for Witze scaling (M, ρ)

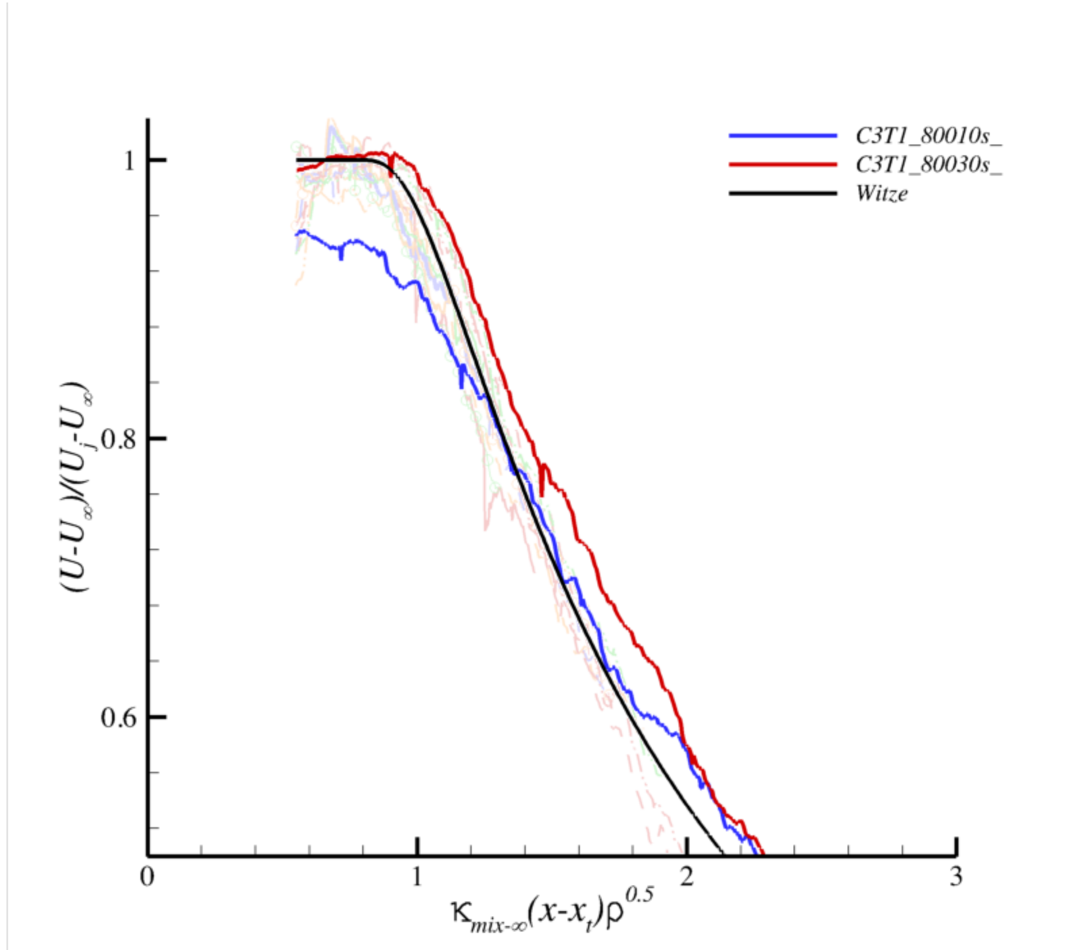
$$(U - U_\infty)/(U_j - U_\infty)$$

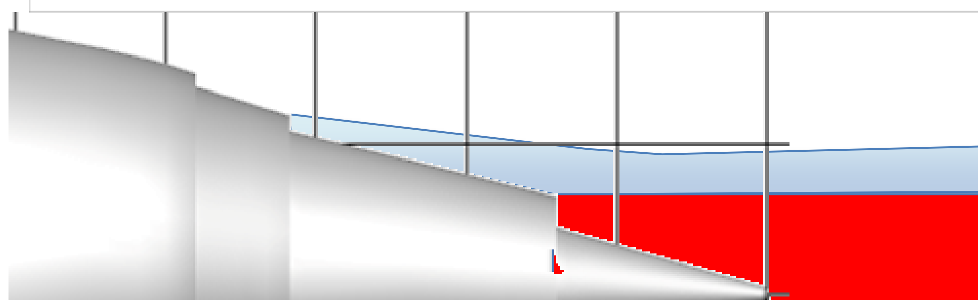
- Using **total flow area** for diameter and **first flowing lip** for origin.
- Matching potential core length.
- Matching decay rate.



Single-stream, complex nozzles

- Two datasets of essentially single-stream plumes from plug nozzle
  - M = 0.9, TsR = 1.0, 2.0
- Using **total flow area** for diameter **and first flowing lip** for origin.
- Not as good match as simple nozzle flows
  - Potential core 'knee' corrupted by wake on cold jet
  - Hot jet has longer potential core than expected
- Examination of flow record shows that some bypass flow (NPR_2 = 1.1, M_2 = 0.4) used on hot dataset.

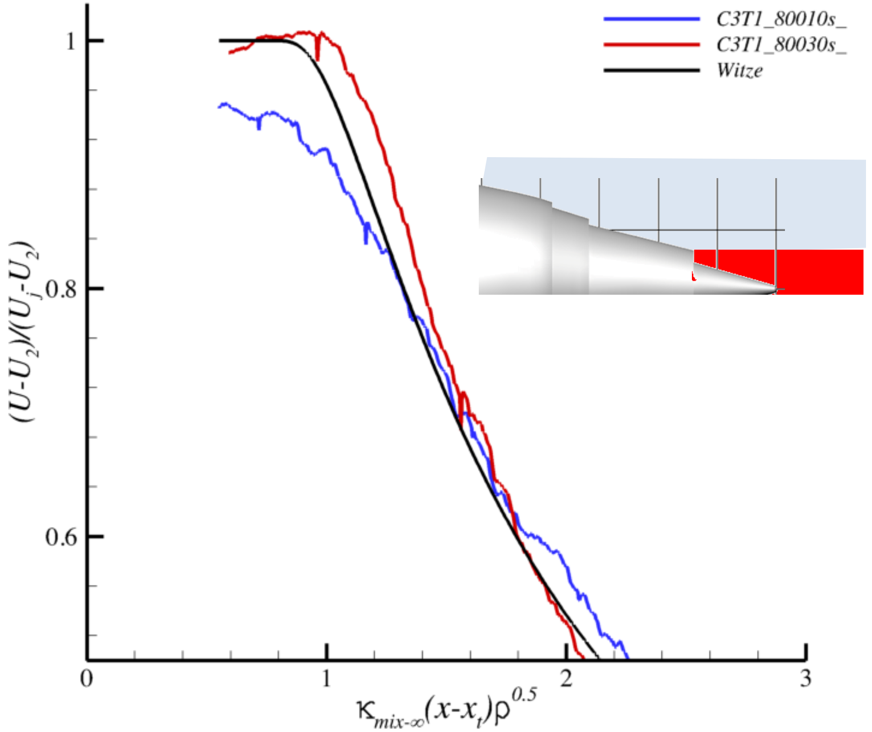




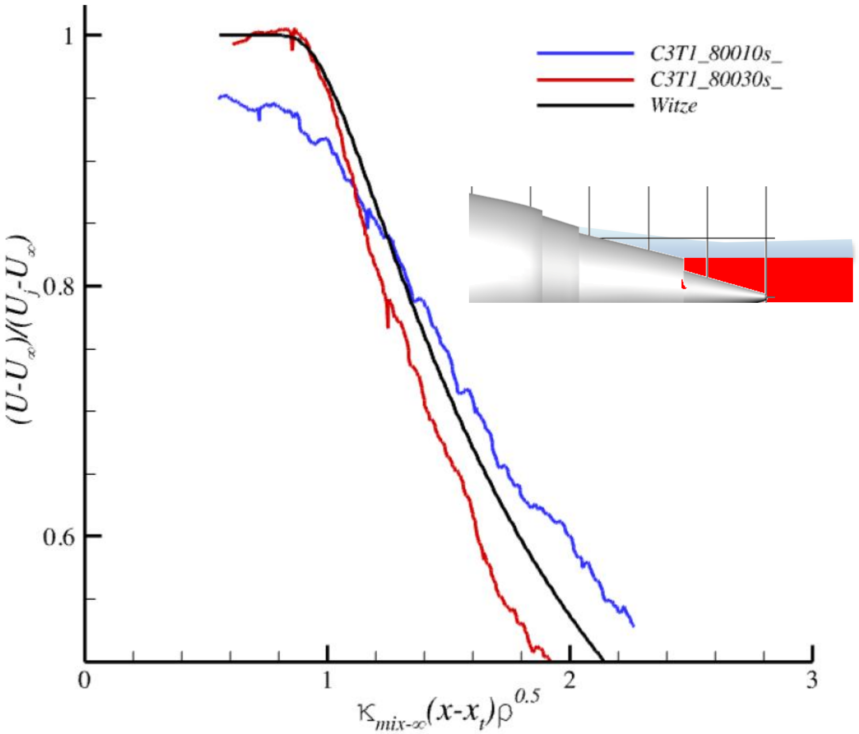
Alternatives for ‘nearly’ single stream case

- Given the slight ($M_2 = 0.4$) flow from the bypass nozzle of the otherwise single-stream hot case, perhaps case should be approximated differently. Two possibilities tried.
- Not really satisfactory.
- Core problem is that small annulus co-flow affects potential core more than plume decay. Calibrated two-parameter model might address this.

Approximate as single-stream jet within $M_\infty = 0.4$ ambient flow

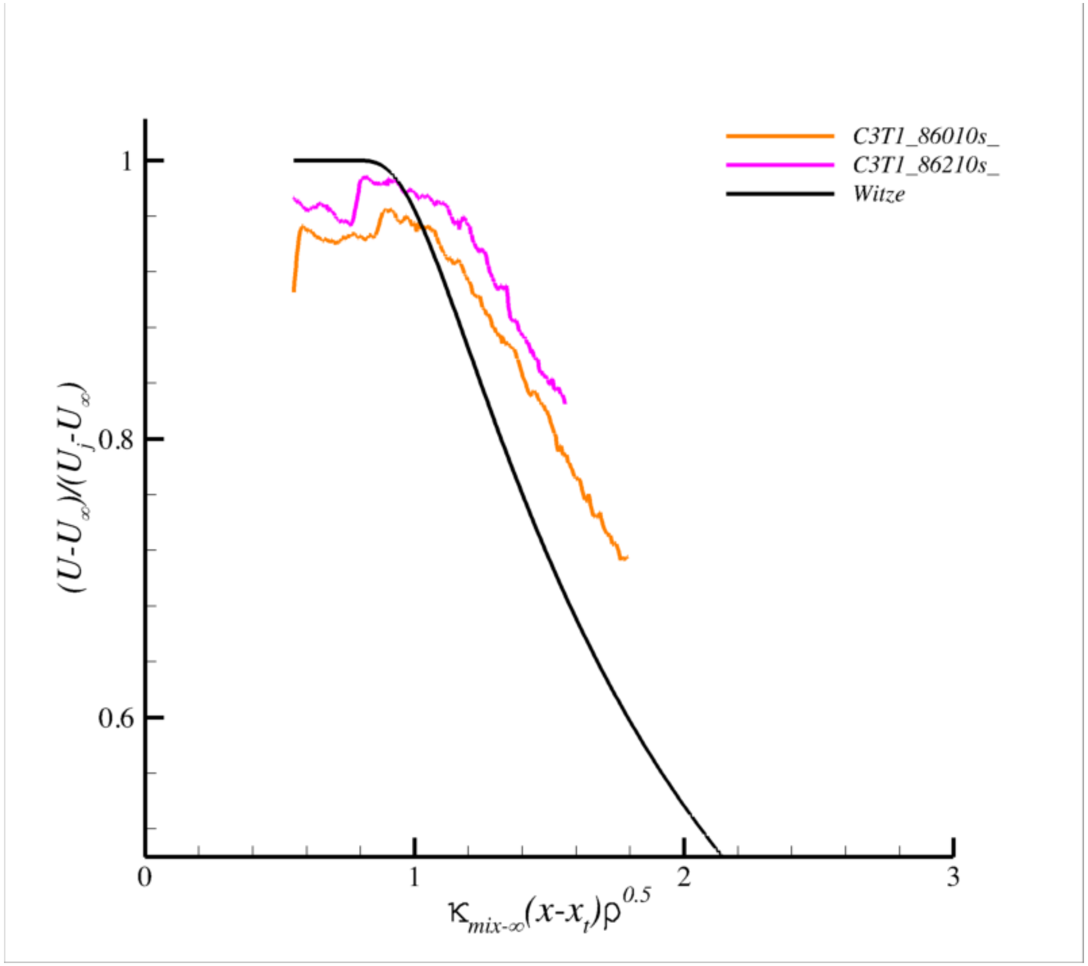


Approximate as static dual-stream jet with small bypass ratio



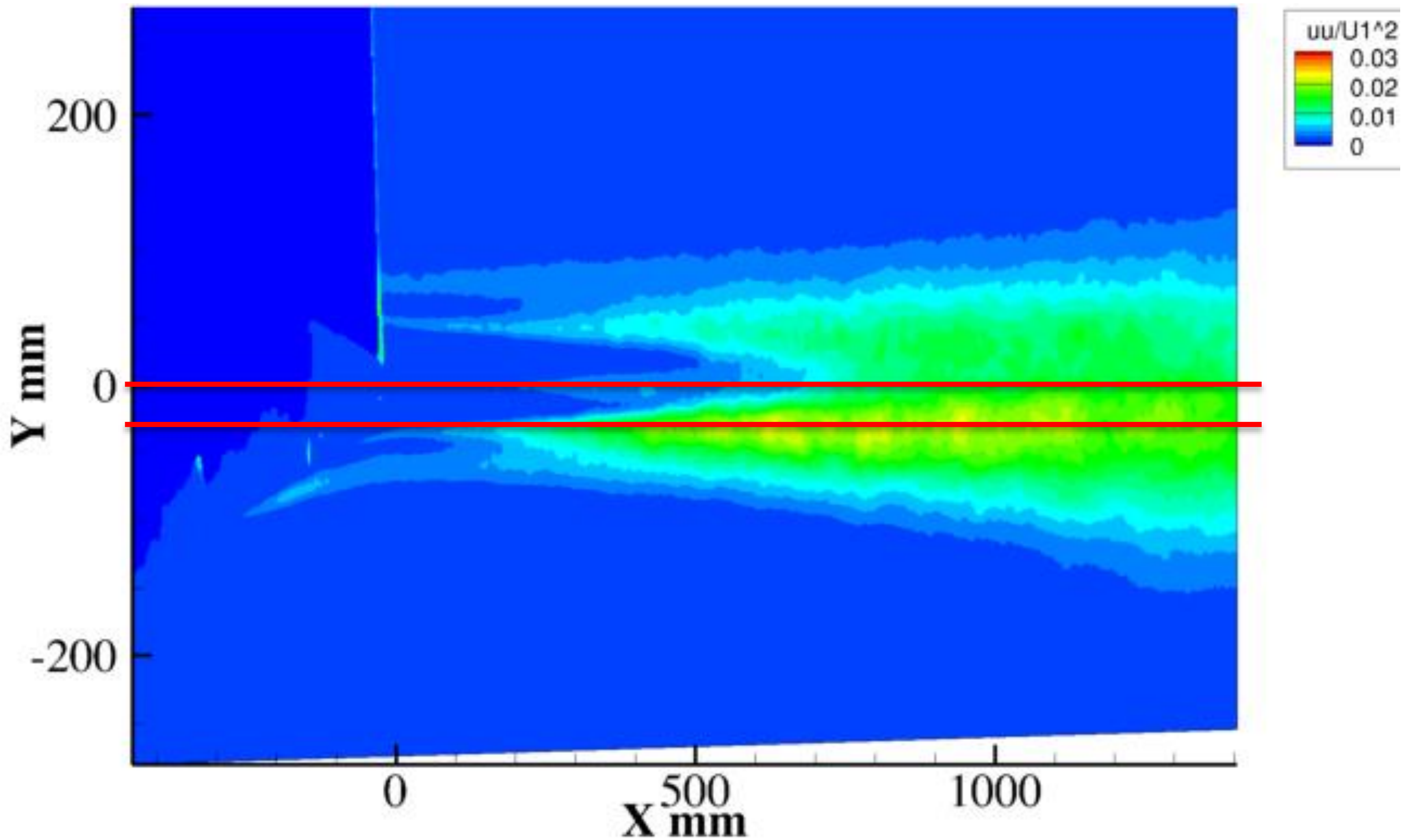
Multi-stream cold jet cases

- Cases with all cold streams
  - $NPR_1 = 1.8$
  - $NPR_2 = 1.6$
  - $NPR_3 = 1.0, 1.2$
- Using **mixed flow** conditions for Witze scaling
- Using **total flow area** for diameter and **first flowing lip** for origin
- Misses core length, decay
- ???!!!



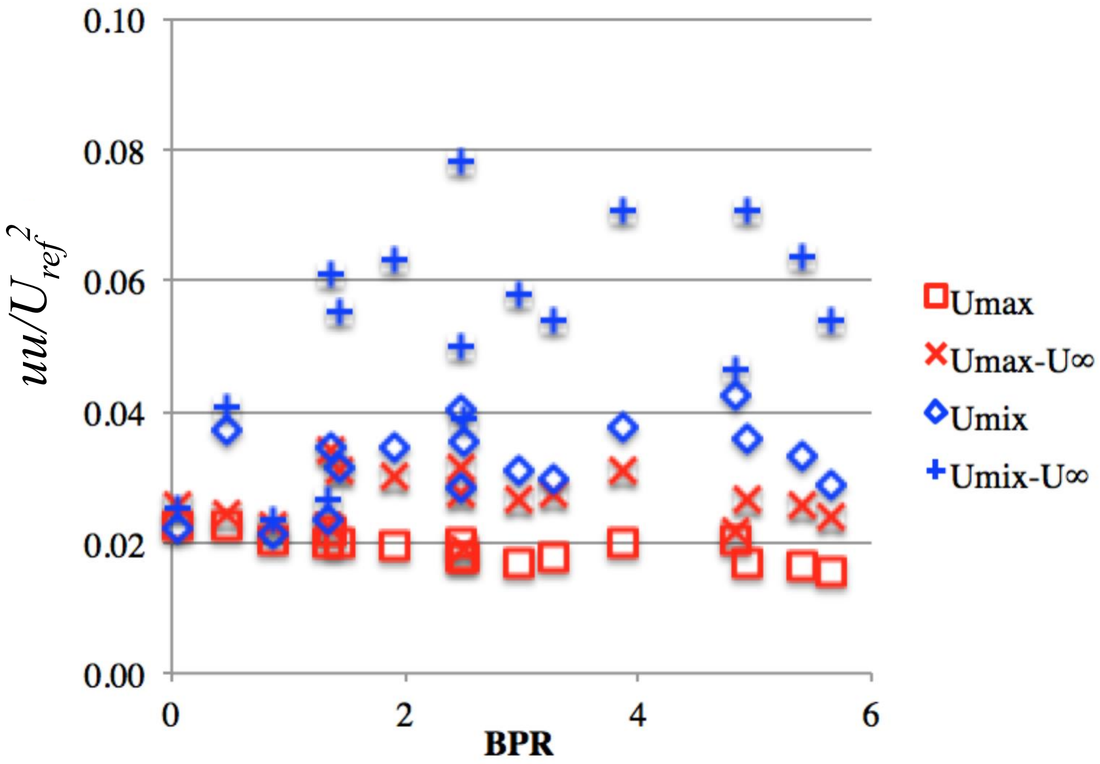
Extracting axial profiles of turbulent velocity

- Axial profiles of uu/U_j^2 extracted on 'centerline' and at radius of peak.



Scaling peak TKE amplitude

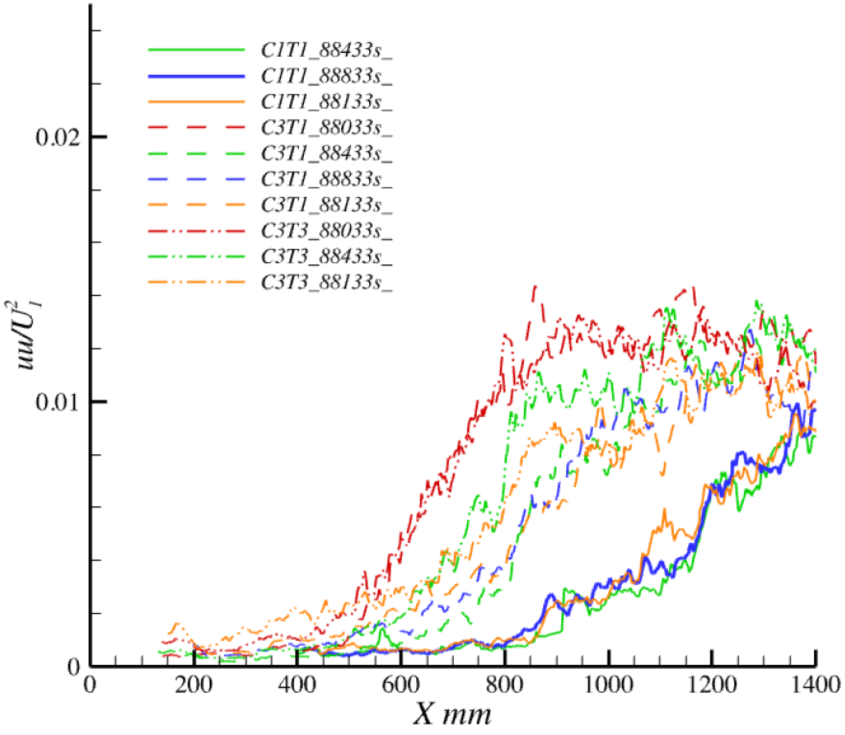
- Radial locations of peak shifts with change in flows, no pattern discernable.
- Peak amplitude uu/U_{ref}^2 best scales with $U_{ref} = U_1$



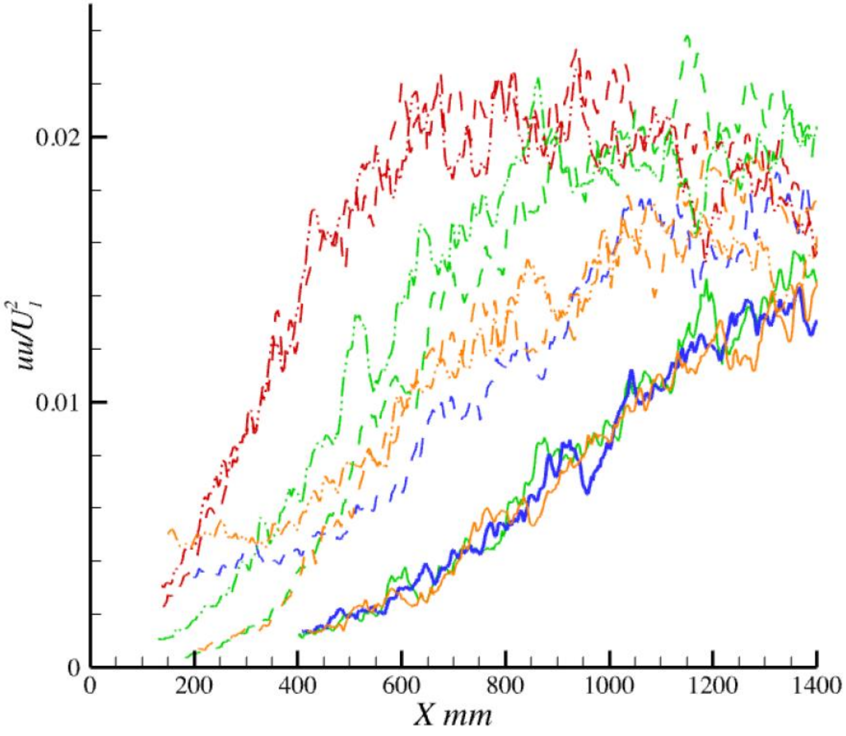
Axial profiles of turbulent velocity

- TKE as extracted along centerline and peak TKE line

Centerline



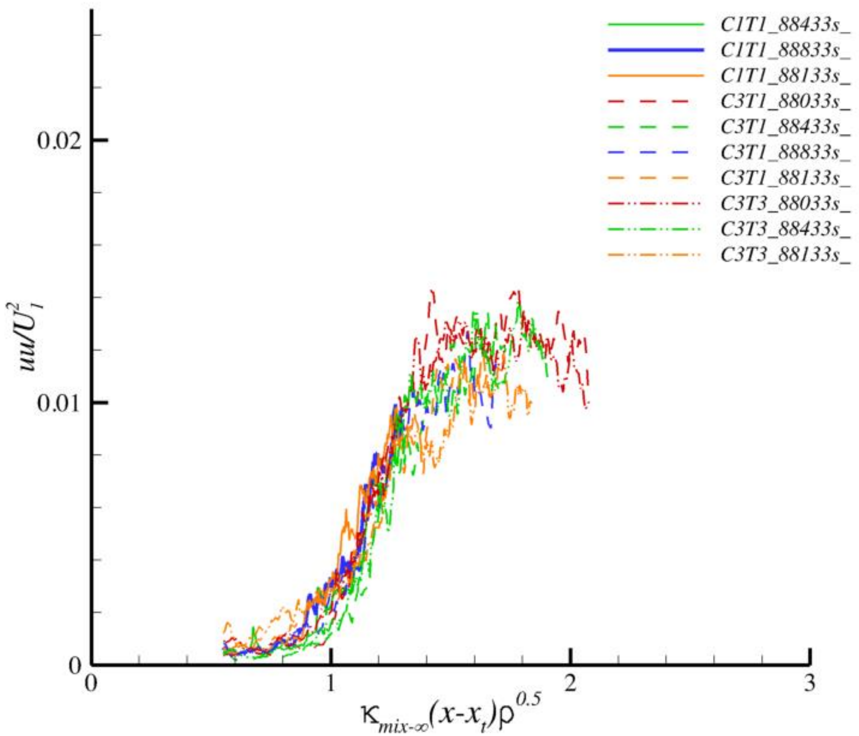
Peak TKE line



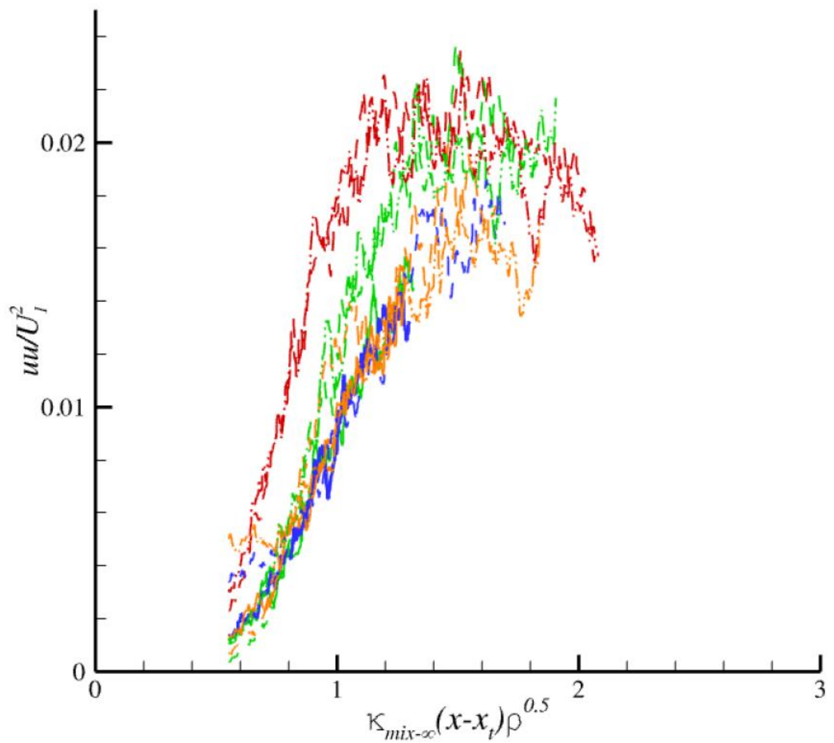
Collapse of axial profiles of turbulent velocity

- Using single-parameter (Witze) scaling the TKE profiles collapse on the centerline
- The TKE profiles on peak line show banding by NPR_3
- Adequate for noise source modeling?

Centerline



Peak TKE line



Summary

- For simple, single-stream jets, a simple two-parameter model collapses centerline velocity profiles better than one-parameter model (e.g. Witze)
- Two parameters can be predicted using flow conditions *Ma*, *TsR* for simple jets.
- Centerline profiles of multi-stream jets can similarly be fitted using two-parameter model.
- Attempts at predicting multi-stream jets using single-stream models only moderately successful.
  - Complicated by complexity of geometry.
  - Impact of secondary (tertiary, ambient) flows different on potential core, decay.
- Best efforts use mix of physical measures of nozzle system:
  - Origin at first flowing nozzle
  - Diameter of total nozzle area
  - For axial profiles, use flow conditions of mixed flow relative to ambient.
  - For peak TKE, use flow conditions of core flow
- Result is a first-order model for plume, and hopefully of noise source distribution in multi-stream jets.
- Validation of jet shielding for three-stream nozzles near surfaces coming soon.